EJECTION MITIGATION USING ADVANCED GLAZING: REPORT TO CONGRESS

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EXECUTIVE SUMMARY

In response to the National Highway Traffic Safety Administration (NHTSA) Authorization Act of 1991 and ongoing research into rollover and ejection mitigation, NHTSA initiated a research program concerning occupant protection in motor vehicle rollover crashes. NHTSA is addressing this occupant protection issue from two perspectives–preventing a rollover from occurring and protecting vehicle occupants during a rollover, including reducing the likelihood of ejections. Almost 65 percent of rollover fatalities occur in the 8 percent of rollovers involving either complete or partial ejection for the occupant fatality. Occupant ejections occur either through structural failures, such as door openings, or through window openings. NHTSA is evaluating the potential of improved door latches, side head air bags, and advanced glazing systems (an automotive industry term for transparent openings) to reduce occupant ejection.

This report summarizes NHTSA's research on advanced glazing research to mitigate ejection through window openings. Each year on average about 7,800 people are killed and 7,100 people are seriously injured because of partial or complete ejection through glazing. Of the fatalities, about 4,800 are associated with vehicle rollovers. The majority of these rollover victims were not using seat belts. In fact, 98 percent of occupants completely ejected and killed during rollover crashes were unbelted.

Advanced glazing systems could save 537 to 1,305 lives annually. Of these, 423 to 1,031 could be prevented by front side glazing and 114 to 274 from back side glazing. In addition, an estimated 235 to 575 serious (MAIS 3-5) injuries could be reduced annually. These estimated benefits would be smaller if seat belt use increases in the future.

Four types of advanced glazings were evaluated: a non-high penetration resistant (HPR) trilaminates, HPR trilaminates, bilaminates, and polycarbonates (rigid plastic). Several companies assisted the agency in manufacturing prototype window system designs for the Ford LTD and General Motors C/K Pickup side doors. These included the E. I. Dupont Company, Advanced Glass Products, Saint-Gobain Vitrage, the Monsanto Chemical Company, the Bayer Corporation, General Electric, Excel Industries, and Pilkington/Libbey-Owens-Ford. The prototype systems included modifications to the front door window frames to provide improved occupant retention, while maintaining the window's ability to be operated. The prototype glazing systems were not intended to be practicable or suitable for production vehicles. One known problem with the proposed designs is they are not applicable to vehicles with frameless side windows.

Preliminary estimates showed an estimated incremental production costs of $48 per vehicle for front side windows if trilaminate glazing were used and $79 per vehicle for front side windows if rigid plastic were used. The projected leadtime was about 3 years. These cost, weight, and leadtime estimates are only applicable to vehicles with framed windows. The final designs tested in this report were not directly evaluated, but should have incremental costs similar to the preliminary estimates.

Three types of impact tests were performed on the advanced side glazing systems. First, NHTSA used an 18 kg (40 lb.) impactor to evaluate potential occupant retention capabilities. Second, the agency used an existing Federal Motor Vehicle Safety Standard 201 free-motion headform to evaluate the glazing systems' potential for causing head injuries. Third, the agency conducted HYGE sled tests with a full-sized dummy to evaluate the glazing systems' potential for causing head and neck injuries.

The results indicated that all but the non-HPR trilaminate had good potential for providing adequate occupant retention. Impacts into the advanced glazings produced similar potential for head injuries as impacts using the current, tempered glass side windows. The neck measurements from impacts into glazings were not repeatable. Despite this wide variability, impacts into advanced glazings resulted in higher neck shear loads and neck moments than those into tempered glass. Impacts into standard tempered glass resulted in axial loads that were comparable to those into the advanced glazings. In each case, the lowest neck injury measurements were from the tempered glass impacts.

Advanced glazing systems have the potential to yield significant safety benefits by reducing partial and complete ejections through side windows, particularly in rollover crashes. However, these safety benefits are not unique to advanced glazing systems, as there are other safety countermeasures that can also prevent ejections. Advanced glazing systems should be evaluated as one component of comprehensive ejection prevention and mitigation strategies that include alternate ejection countermeasures such as the more recent developments in inflatable head protection and/or rollover protection systems.

1.0 INTRODUCTION

1.1 Background

The National Highway Traffic Safety Administration (NHTSA) published two Advanced Notices of Proposed Rulemaking (ANPRMs) in 1988 announcing that the agency was considering making a proposal of requirements for passenger vehicles intended to reduce the risk of ejections in crashes where the side protection of the vehicle was a relevant factor. One notice (53 FR 31712, August 19, 1988) dealt with passenger cars. The other notice (53 FR 31716, August 19, 1988) dealt with light trucks. The agency reported that a significant number of fatalities and serious injuries involved the partial or complete ejection of occupants through the doors or side windows.

The agency reported at the time that based on the 1982-1985 Fatality Analysis Reporting System (FARS), 19.5 percent of the fatalities each year were from complete ejection and 4.3 percent were from partial ejection of the occupant through glazing. Data from the National Crash Severity Study (NCSS) showed that for passenger car occupant fatalities involving ejection, 34 percent were ejected through the side windows. Several studies had shown that ejection increases the probability of an occupant's death or serious injury several times over that of non-ejected occupants[4].

NHTSA believed that new side window designs, incorporating different glazing/frames, may be able to reduce the risk of ejections. The agency pointed out that windshields already contained an inner layer of plastic that mitigated ejection. It was thought that either trilaminate windshield-type glass or side glass with an additional inner layer of plastic may be suitable materials to mitigate ejection. Agency researchers also developed a method of anchoring these glazings to the window frame. The plastic portion of the glazing would have to be encapsulated in a frame. The frame could be designed to accommodate movable windows.

At that time, NHTSA suggested that one performance approach would be to use a 18 kg (40 lb) glazing impact device, requiring that it not penetrate the plastic layer of a side window at 32 kmph (20 mph), an estimated typical contact speed.
Numerous comments were received on the 1988 ANPRM. Major issues were raised concerning the proposal, primarily that the safety benefits were not quantified. Others were that the injury criteria were not specified for side impact, the practicability of glazing designs were questioned and had never been demonstrated, the cost was high, and there was no objective and repeatable test procedure proposed. Finally, the comments questioned what effect ejection mitigating glazing would have on overall occupant injuries and fatalities, and whether this material would actually increase injuries in belted occupants.

The National Highway Traffic Safety Administration Authorization Act of 1991 mandated that the agency initiate rulemaking on rollover protection. To fulfill this requirement, the agency published an ANPRM on January 2, 1992, (57 FR 242) soliciting information concerning rollover crashes, to assist the agency in planning a course of action on several rulemaking alternatives. Forty-two comments were received from vehicle manufacturers, safety groups, retailers of aftermarket automotive equipment, automotive consultants, and a concerned citizen.

Subsequently, a Rulemaking Plan titled "Planning Document for Rollover Prevention and Injury Mitigation Docket 91-68 No. 1" was published for public review on September 29, 1992, (57 FR 44721). The planning document outlined crash avoidance and crashworthiness rulemaking approaches to reduce rollover-related injuries and fatalities. This document included a section concerning ejection mitigation using glazing.

Public comments on the glazing program were received from three organizations: Motor Vehicle Manufacturers Association (MVMA), Chrysler Corporation (Chrysler), and Mitsubishi Motors Corporation (DOT Docket NHTSA-1996-1683, available at dms.dot.gov). These comments were similar to the comments on the 1988 ANPRM. The commenters questioned design practicability, the lack of standardized testing, and the potential for additional contact injuries.

NHTSA continued its research program and in November 1995 issued a report titled "Ejection Mitigation Using Advanced Glazings: A Status Report"[1]. This report documented research which established the problem size and potential benefits of preventing occupant ejection through the front side windows during automotive crashes. A prototype glazing system consisting of a modified door and glazing materials was designed and demonstrated. This glazing system was designed to use higher strength window materials to withstand the force of an occupant impact and to transfer impact forces from the glazing to the door and window frame of the vehicle. The prototype advanced glazing system was able to successfully retain an 18 kg (40 lb) mass impacting at 24 kmph (15 mph). This impact test was determined to be representative of the type, shape, and speed that could be expected during side impact and rollover crashes. The prototype glazing system was tested using a variety of window glazing materials, bilaminates, trilaminates, and polycarbonates (rigid plastics), to assess a wide range of performance characteristics. Additionally, this research used the FMVSS 201 free-motion headform (FMH) to evaluate the potential for head injury to an occupant due to glazing impact. Preliminary testing with the FMH indicated a low potential for head injury from contacts with the prototype glazing system.

A public meeting was held to present and discuss this research program. NHTSA received numerous comments from this public meeting and, based on these comments, extended the research program (DOT docket NHTSA-1996-1782). In November 1999, NHTSA issued a report titled “Ejection Mitigation Using Advanced Glazings: Status Report II”[2]. This report extended several aspects of the previous research. A more current door/glazing system was evaluated using a variety of glazing materials. A series of sled tests was conducted to evaluate the potential for neck injury from the use of advanced glazing systems. Additional tests were conducted to evaluate the feasibility issues of using the 18 kg and FMH impactor component tests. The benefits analysis was also updated to include the newest data and to address comments received in response to the previous report. On July 19, 2000 (65 FR 44710) NHTSA published a request for comments to the agency’s second advanced glazing status report (DOT docket NHTSA-2000-7066). The closing date for comments was November 16, 2000. NHTSA received 96 comments from auto manufacturers, suppliers, safety groups, a vehicle extraction specialist, an engineering service and private individuals. NHTSA has carefully analyzed the information provided in the comments. The automotive manufacturers recommended that NHTSA focus on occupant containment efforts by means of side curtain airbags. All other commenters believed that advanced glazings would enhance overall safety performance of vehicles. The private citizens did not provide technical data but favored the use of advanced glazing in side and rear windows of vehicles.

Since the publication of the second status report, NHTSA has continued its research activities. This research included an evaluation of the effect of impactor test speed to assess the level of door frame modifications required, and the resulting effect on the potential for producing head injury. Also, the effect of roof and door frame damage on the occupant retention capability of advanced glazing systems was examined. Finally, further evaluation was conducted into the neck injury causing potential of advanced glazing systems. This recent research has been incorporated into this report.

NHTSA is evaluating the ejection mitigating potential of other, non-glazing systems, such as inflatable head and/or rollover protection devices. This is an ongoing research project. A discussion of the preliminary research is included in section 9, but substantial research results are not expected until the end of fiscal 2001.

In 1996, as a parallel effort to NHTSA's in house programs, NHTSA, PPG Industries, and the General Services Administration (GSA) joined together to conduct a small GSA fleet study to evaluate the performance of bilaminate and trilaminate side windows. The goal of this study was to evaluate the in-use behavior of laminated side windows. The GSA vehicle locations were selected in order to evaluate vehicles that were driven regularly and subjected to a variety of climates. Vehicle examinations were conducted approximately every six months to physically inspect the windows and interview the drivers. Forty-eight driver side windows were installed in government vehicles, mostly military police vehicles, in three locations on the east coast. Approximately equal numbers of trilaminate and bilaminate were installed at each location. The locations chosen were Ft. Drum, NY, Washington, DC, and Orlando, FL. The military vehicles were generally high mileage vehicles, often used 24 hours a day. These GSA furnished vehicles were only in use for 2 to 3 years, however it was felt that these vehicles did provide insight into the durability of the laminated side windows.

Both single driver and fleet vehicles were used in this study. The single driver vehicles were driven an average of 15,000 miles, while the fleet vehicles averaged 250,000 miles. In general, most drivers of the fleet vehicles were unaware that the side windows were not standard and noticed no difference in performance. The drivers who had a vehicle assigned to them were informed of the laminated windows, but they also observed no difference in performance. Inspections by the glazing manufacturer, PPG, were conducted twice a year throughout the study and, at the end of the study, the glazings were removed and evaluated in PPG's laboratory. These inspections noticed scratches on approximately 50 percent of the bilaminate (glass-plastic) windows. None of the scratches affected visibility or were reported by the drivers. They were only detected by the manufacturer's representative. One trilaminate side window was broken during the replacement of the window regulator, and the window was replaced with a new trilaminate side window. Upon removal and inspection, there were some additional technical anomalies with the performance of the laminated edges. None of these concerns affected the performance of the side windows. A report on this fleet study is under development and is expected to be released in April 2001.

1.2 Problem Definition

Overview - There were 32,091 fatalities among occupants of light vehicles in 1999, and an estimated 7,636 of these fatalities (24 percent) were ejected through glazing. This includes 4,812 fatalities who were completely ejected and 2,824 fatalities who were partially ejected. Partial or complete ejection through glazing accounted for 4,772 fatalities in rollover crashes, or 52 percent of the rollover fatalities in 1999. From 1995 through 1999, an average of 32,501 light passenger vehicle occupants were completely ejected each year. Of these,18,508 (57 percent) were ejected through glazing, with 9,684 (30 percent) being ejected through front side windows. Sixty percent of the occupants who were completely ejected through non-windshield glazing were ejected through a front side window.

General Ejection Statistics - The 1999 Fatality Analysis Reporting System (FARS) and the 1995 through 1999 National Automotive Sampling System (NASS) were reviewed to determine the number of injuries and fatalities associated with ejection from light motor vehicles and, specifically, ejection through motor vehicle windows. The FARS data include a report of each fatal crash that occurred on a public access road in the 50 states and the District of Columbia. The NASS data are based on a detailed investigation of a sample of police-reported towaway crashes, conducted by 24 field research teams; NASS investigates about 6,400 light vehicle crashes a year.

Initially, all ejection-related fatalities were identified, regardless of ejection route. The 1999 FARS data include 32,091 people who were killed as occupants of cars, light trucks, passenger vans, or utility vehicles. Twenty-eight percent of these fatalities were reported to have been ejected from the vehicle; 22 percent were completely ejected and five percent were partially ejected. (Partial ejection is defined as having some portion, but not all, of the occupant's body outside the motor vehicle during the crash.) The FARS data are shown in Table 1.1.

Table 1.1 -- Ejection Status for Occupant Fatalities in Light Passenger Vehicles in 1999 FARS

Event	Fatalities	Percentage
Not ejected	23,113	72%
Completely ejected	7,144	22%
Partially ejected	1,719	5%
Unknown whether ejected	115	-
Total	32,091	100%

The NASS data are more detailed, but they are based on a sample of cases. The annual average fatality estimate from the 1995-1999 NASS data is 16 percent lower than the 1999 FARS count: 27,017 estimated from NASS compared to 32,091 counted by FARS. NASS and FARS agree that 22 percent of occupant fatalities were completely ejected from the vehicle, but the NASS data suggest that FARS does not identify half the partial ejections (an estimate of 10 percent from NASS compared to the five percent reported to FARS).

NASS data are most useful for showing percentage distributions of subcategories of the crash events. Therefore, in the following analyses and discussions, the total number of fatalities, as identified in the 1999 FARS database, was used as the basis total, and percentages based on the 1995-1999 NASS fatality estimates were used for distributions of this total. The NASS estimates of non-fatal involvements were not adjusted because these represented the best estimate of annual occurrences. Also, there were some missing data in the NASS ejection reporting (unknown ejection status, degree, and route). Therefore, to avoid producing estimates that were too low, these were distributed into the various categories using a strategy developed to improve the ejection estimates.

In 1999, an estimated 32 percent of fatalities were partially or completely ejected through all vehicle openings (Table 1.2), accounting for 10,302 fatalities. Ejection rates were lower among seriously-injured survivors (that is, among survivors with an Abbreviated Injury Scale[3] (AIS) rating of 3 or greater). An estimated eight percent of seriously-injured survivors were completely ejected and two percent were partially ejected. About one percent of all occupants of light vehicles that were in towaway crashes (without regard to injury outcome) were ejected, which is an estimated 51,078 partial and complete ejections per year. This pattern was consistent with previous research. For example, Winniki[4] showed that ejection is associated with an increased risk of fatality.

Table 1.2 -- Ejection Status for Occupants of Light Vehicles
Annual Average for 1995-1999 NASS, Fatalities Adjusted to 1999 FARS

Fatalities			
	Cases	**Estimate**	**Percentage**
Not ejected	1,598	21,789	68%
Completely ejected	456	7,177	22%
Partially ejected	241	3,125	10%
Unknown degree	10	distributed	distributed
Unknown if ejected	55	distributed	distributed
Total	2,360	32,091	100%
Seriously-Injured Survivors			
	Cases	**Estimate**	**Percentage**
Not ejected	4,221	89,896	90%
Completely ejected	418	7,494	8%
Partially ejected	165	2,074	2%
Unknown degree	14	distributed	distributed
Unknown if ejected	94	distributed	distributed
Total	4,912	99,463	100%
All Occupants			
	Cases	**Estimate**	**Percentage**
Not ejected	48,089	5,158,302	99.0%
Completely ejected	1,527	32,501	0.6%
Partially ejected	726	18,577	0.4%
Unknown degree	55	distributed	distributed
Unknown if ejected	801	distributed	distributed
Total	51,198	5,209,380	100.0%

Injury Outcome for Glazing Ejections - From 1995 through 1999, there were an estimated 7,636 fatalities and 6,894 seriously-injured survivors ejected through glazing each year. Table 1.3 shows a breakdown by injury severity and ejection degree, indicating that both partial and complete ejections present a safety problem. Partial or complete ejections through light vehicle windows were associated with 24 percent of fatalities and seven percent of serious injuries.

Table 1.3 -- Injury Severity for Ejections through Glazing

Annual Average for 1995-1999 NASS, Fatalities Adjusted to 1999 FARS

	Fatality	Serious injury	Lesser Injury	Total
Complete ejection	4,812	4,988	8,709	18,508
Partial ejection	2,824	1,906	12,054	16,784
Total	7,636	6,894	20,763	35,293

Glazing Ejection Routes - From 1995 through 1999, there were an estimated 32,501 complete ejections per year, and 18,508 (57 percent) of these were through glazing (Table 1.4). The most common window ejection routes were the right- and left-front side windows, which accounted for 30 percent of all complete ejections. The left- and right-side front windows accounted for 60 percent of the non-windshield glazing complete ejections. High-penetration-resistant (HPR) windshields, which were designed to mitigate ejection, accounted for eight percent of complete ejections. Glazing was the ejection route for 90 percent of partial ejections. This included 11 percent who were partially ejected through the windshield and 62 percent who were partially ejected through a front side window.

The majority of the 10,302 fatalities who were partially or completely ejected in 1999 were ejected through glazing. There were 7,636 fatalities who were ejected through glazing, including 4,812 who were completely ejected and 2,824 who were partially ejected. Of these, 3,175 of the complete ejection fatalities and 2,208 of the partial ejection fatalities, totaling 5,383 lives, involved ejection through the left- and right-front side windows.

Four percent of the partial and complete ejections were through roof glazing (Table 1.4), even though only 11 percent of all light vehicles in towaway crashes in 1999 had a roof window. If every light vehicle had a roof window, the number of ejections could increase dramatically. For example, there were 1,116 + 993 = 2,109 partial and complete ejections through roof glazing. If this were expanded to every light motor vehicle, there could theoretically be 18,500 roof glazing ejections per year, calculated as 2,109 / 0.114. This suggests that occupants are very susceptible to ejections through roof glazing because of the direct ejection path for the driver and right-front passenger.

Table 1.4 -- Ejection Route for Occupants Ejected from Light Passenger Vehicles

Annual Average for 1995-1999 (NASS), Fatalities Adjusted to 1999 FARS

	Complete Ejection			Partial Ejection		
	Cases	Estimate	Percent	Cases	Estimate	Percent
Windshield	67	2,465	8	94	1,954	11
Front Windows	420	9,684	30	416	11,564	62
Back Windows	75	2,243	7	47	1,641	9
Backlight	103	2,880	9	25	614	3
Roof Window	28	1,116	3	14	993	5
Other Glazing	7	122	0	3	19	0
Unknown Glazing	3	distributed		0	distributed	
Not Glazing	488	13,992	43	69	1,793	10
Unknown Route	336	distributed		58	distributed	
Subtotal-Glazing	703	18,508	57	599	16,784	90
Totals	1,527	32,501	100	726	18,577	100

Rollover Versus Non-rollover Crashes - From 1995 through 1999, an estimated 5,209,380 occupants were involved in light vehicle towaway crashes each year, including 419,813 in rollover crashes. There were 9,123 fatalities in rollovers in 1999. (Most of the other 22,968 fatalities in 1999 occurred in front, side, or rear crashes.) Of these rollover fatalities, 4,772 involved complete or partial ejection through glazing (Table 1.5 and Figure 1.1).

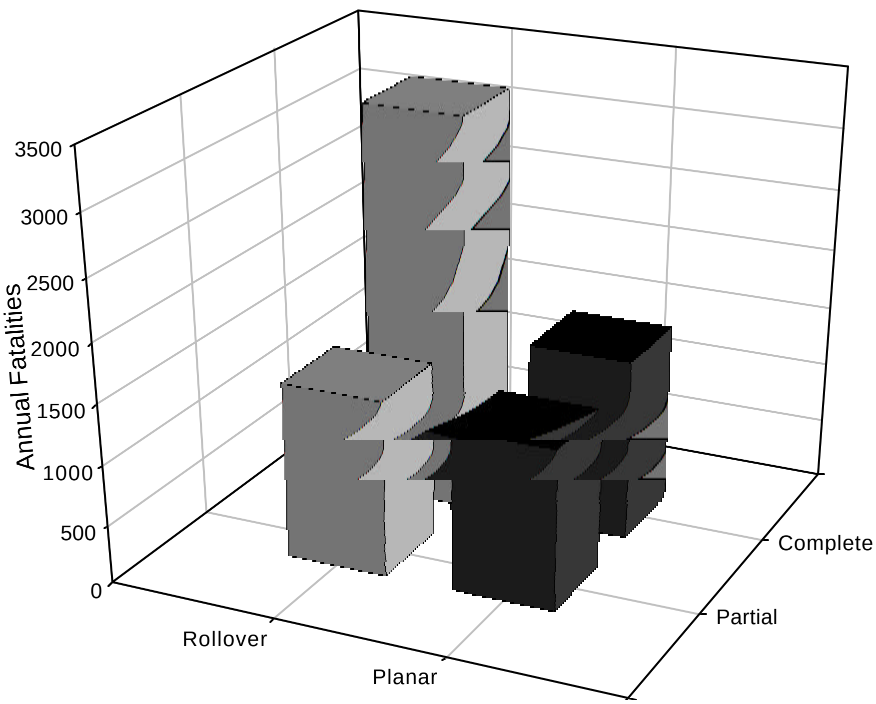
Ejections are not unique to rollover. There were 2,864 complete and partial ejection fatalities in planar (non-rollover) crashes. A total of 7,636 people were killed in crashes involving partial or complete ejection through glazing in 1999. Sixty-two percent of the glazing ejection fatalities occurred in a vehicle rollover and 38 percent were in non-rollover (planar crashes).

Table 1.5 -- Fatal Glazing Ejections

Annual Average for 1995-1999 NASS, Fatalities Adjusted to 1999 FARS

	Rollover	Planar	Total
Complete Ejection	3,295	1,516	4,812
Partial Ejection	1,476	1,348	2,824
Total	4,772	2,864	7,636

Fatal Glazing Ejections
Annual Average for 95-99 NASS, Adjusted to 99 FARS



Vehicle Type - The number of ejections as a function of vehicle type were estimated. From 1995 through 1999, there were an average 51,078 partial and complete ejections per year. About 35,293 of these were through glazing. Table 1.6 shows higher ejection rates for pickup trucks and sport utility vehicles than for passenger cars and vans.

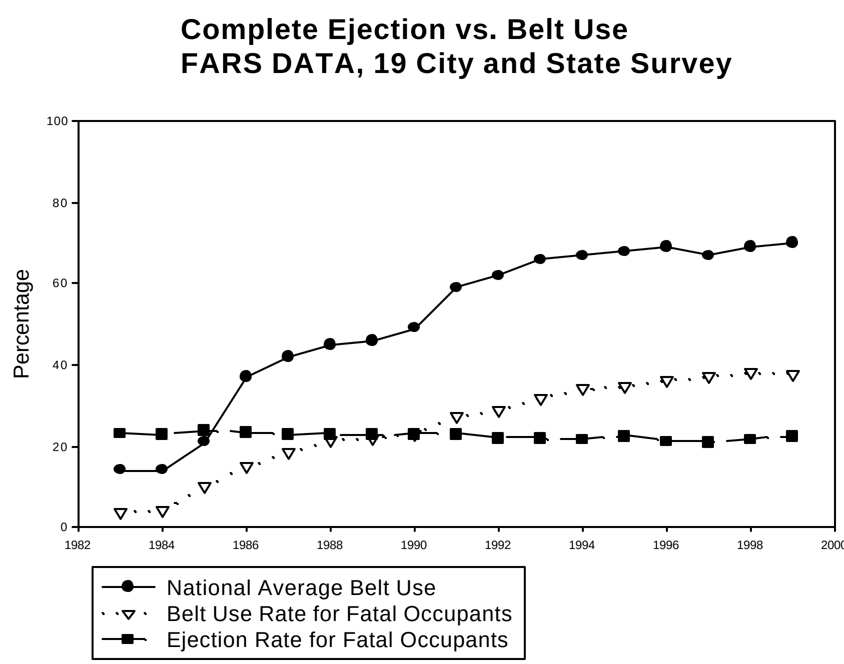
Table 1.6 Glazing Ejections by Vehicle Type. Annual Average for 1995-1999 NASS, Fatalities Adjusted to 1999 FARS					
	Partial Ejection	Complete Ejection	All Ejections	All Occupants in Crashes	Glazing Ejection per 1,000 Occupants
passenger car	9,917	8,501	18,417	3,782,316	5
utility vehicle	2,326	3,182	5,508	449,353	12
vans	468	1,772	2,340	409,336	6
pickups	4,014	5,023	9,036	531,590	17
other/unknown	60	31	91	12,366	7
total	16,784	18,509	35,293	5,209,380	7

<u>Injuries by Body Regions</u> - It is necessary to look at moderate injuries (AIS of 2 or greater) in order to separate injuries by body region and get enough injured occupants for the results to be statistically significant. For complete and partial ejections, the greatest number of moderate injuries from all vehicle contact sources was to the torso (42 percent of the moderate injuries among those completely ejected and 38 percent among those partially ejected). Head injuries were 35 percent of moderate injuries among those completely ejected and 39 percent of injuries among those partially ejected. Moderate injuries were less common for legs, arms, and the neck. Neck injuries were four percent of the moderate injuries among ejected occupants.

Thirty-four percent of the moderate injuries among those ejected through a windshield (with its penetration-resistant qualities) were to the head, and another six percent were to the neck. It is not clear whether these injuries are caused by the penetration resistance of the glazing or the kinematics of an ejection through the windshield.

Belt Use Versus Ejection - Virtually all completely ejected people are unbelted. In one analysis[5] the agency determined the belt use of ejected drivers, using the 1989 FARS data. That study indicated 98 percent of the completely ejected drivers and right front passengers were unbelted.

In order to determine the effect of increased seat belt use on the reduction of occupant ejections, the two sets of data were compared. As shown in Figure 1.2, increased seat belt use has not caused a concurrent decrease in ejected, fatally-injured occupants[6]. The agency has observed this phenomenon for many years. It may be due to the continued non-use of drivers involved in high speed crashes where ejection is likely. Those occupants most likely to be involved in fatal crashes are least likely to use a seat belt. This problem continues to be addressed by NHTSA as part of its efforts to increase seat belt use.



2.0 OBJECTIVE

The purpose of this report is to document the research conducted to evaluate the feasibility and benefits of using advanced glazing systems to reduce the number of occupant ejections in light passenger vehicle crashes. Crash data were analyzed to determine the size and scope of the ejection problem on the nation's roadways. Test procedures were developed to evaluate the potential for advanced glazing systems to reduce occupant ejections, without producing additional head and neck injuries. With this information, the potential safety benefits from advanced glazing systems were estimated.

3. ADVANCED SIDE GLAZING SYSTEMS

This section describes prototype systems for automotive sidelites used in the NHTSA's Advanced Side Glazing research program for occupant ejection mitigation. The research objectives bring together the technologies of glass makers, polymer resin suppliers, and automotive modular window suppliers in a joint effort to develop a cost effective occupant retention glazing system with the capabilities to meet the performance criteria. Several outside companies assisted the agency in manufacturing prototype window system designs for the Ford LTD and General Motors C/K Pickup side doors. These included the E. I. Dupont Company, Advanced Glass Products, Saint-Gobain Vitrage, the Monsanto Chemical Company, the Bayer Corporation, General Electric, Excel Industries, and Pilkington/Libbey-Owens-Ford.

The success of the side glazing modular system to contain the targeted energy levels is highly dependant upon how well the applied energy is transferred from the glazing material to the door frame without encountering failure of the glazing material, failure of the adhesive bond between the glazing material and the framing module, or failure at the framing module/window channel interface. Currently, tempered glass is used in automotive side windows, which offers virtually no resistance to occupant ejection.

3.1 Side Glazing Candidates

The glazing materials were selected to evaluate a range of glazing characteristics and any effect they may have on ejection mitigation or occupant impact injury. Other potential safety concerns such as laceration, entrapment, or durability were not evaluated in this report. Many of these safety concerns are addressed by the existing standards for automotive glazings.

In the early phase of this research, several different advanced glazings were examined for use with the Ford LTD side door. The details of those glazings are discussed in the 1995 status report[1]. In the later phase, several other advanced glazings were examined for use with the Chevrolet C/K Pickup side door. The following discussion describes these later glazings.

<u>Tempered glass</u> - Performance parameters are well established for tempered sidelites whose primary function is in creating a vision area. Due to the high stiffness (modulus) of glass, flexing does not occur during impact, and the tempered glass does not absorb the occupant's energy. Normally, the window breaks. Tempered glass offers little resistance to occupant ejection once it has been fractured.

<u>Glass-Plastic Glazing</u> - This construction consists of a glass-plastic laminated construction (hereafter referred to as bilaminate) in which a thin plastic film is bonded to the glass. In these formulations, the plastic film actually consist of two or more polymers bonded together resulting in desired performance properties. The specific bilaminate glazing is commercially known as *SentryGlas®*. This product is made by laminating a layered composite of polyvinyl buteyral (PVB, 0.76 mm) and a polyester (0.25 mm) coated with an abrasion resistant coating, bonded onto a standard 4 mm OEM tempered glass sidelite.

<u>Laminated Glazing</u>- Three-layer laminated construction is similar to conventional windshields in which a plastic film is laminated in between two glass layers (hereafter referred to as trilaminate). Various trilaminate configurations were tested at various stages throughout the

research program. Both a high penetration resistant (HPR) polyvinyl butyrl (PVB) formula, with relatively the same mechanical properties as found in windshields (referred to as HPR trilaminate), and a higher adhesion PVB formula (referred to as non-HPR trilaminate) were used. The construction consisted of two 1.84 mm glass plys sandwiching a 0.76 mm PVB film. The trilaminate glass plys were heat strengthened. Heat-strengthened glass has characteristics somewhere in between fully tempered and annealed glass. Heat strengthening the glass allows for the thinner glass plys to provide adequate strength while keeping the same overall thickness as that of a standard tempered glass window.

A stiffer laminated glazing was evaluated in later rounds of testing. In this construction, an ionoplast with approximately 100 times the stiffness of PVB was used in place of the PVB interlayer. This product is commercially available and is known as *SentryGlas® Plus*.

Monolithic Plastic - Although various rigid plastics have been considered for possible replacement of automotive body glass, they are currently restricted to areas not requisite for driving visibility, due in part to durability issues. However, because the NHTSA has received considerable interest from the plastics industry, and the goal of developing a more complete understanding of glazing system performance, rigid plastics were included in the research. The rigid plastic used was a polycarbonate that was thermoformed to match the curvature of the standard tempered glass part. It was not treated with an abrasion resistant hard coating.

3.2 Window Encapsulation

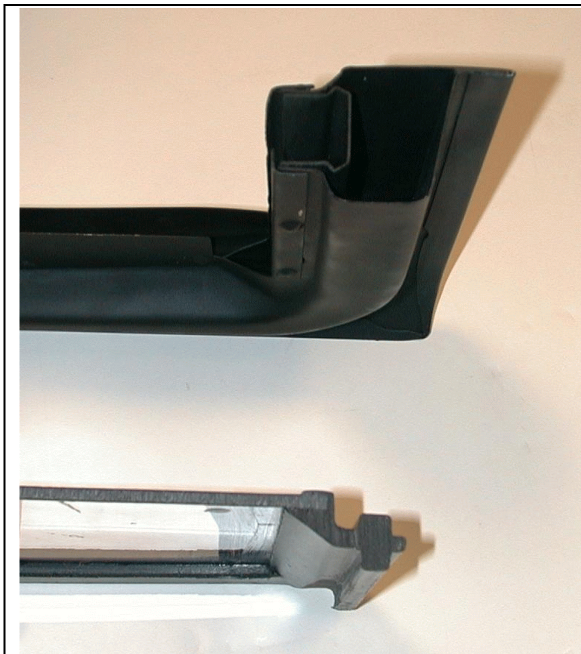
To achieve the greatest penetration resistance from advanced glazings, the window system must transfer the impact load to the window frame. This is achieved through the use of modular windows. Modular windows are made by encapsulating the window's perimeter with a plastic frame usually made of polyurethane or polyvinyl chloride (PVC).

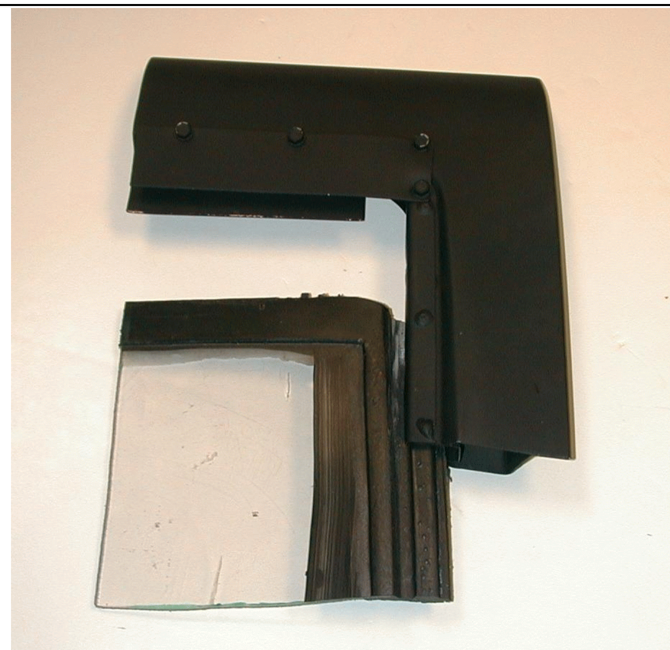
In this program's earliest work, a polyurethane frame was conceived that would not add to the width of the glass, allowing the modular glazing to be set inside the existing window frame of the Ford LTD. This "L-edge" did not impede the ability to raise and lower the glazing. It was concluded that it would be highly desirable to have a modular glazing structure with containment capabilities in which the top and diagonal edge did not require framing. This configuration would seem to be more acceptable to automobile manufacturers for future designs of flush mounted side glass systems. The advanced glazings in this earlier work were therefore encapsulated only along the two vertical edges.

Although the LTD sidelites were no longer in production, the shape represented by the two vertical edges represents a large majority of sidelite designs in today's vehicles. With 45 percent of the glazings perimeter being constrained (this includes the bottom edge of the glazing which is attached to the window regulator), the performance of the glazing module was assessed as a worst case.

This initial encapsulation design was conducted for a single older model vehicle that was no longer in production, making it increasingly difficult to obtain windows and doors for testing. It was decided to extend the encapsulation design and subsequent testing to a newer model vehicle with a larger size of side window glazing.

An existing mold used to encapsulate the vertical edges of the General Motors C/K Pickup truck sidelite was modified to produce a "T-edge" frame along the vertical edges that fit inside the A and B-pillar, so as to make the glazing "flush" with the door and window frame. The T-edge design allowed for both vertical edges to fit in the existing C-channel of the door/window frame. This results in increased penetration resistance because impact loads are transferred to the door/window frame. In addition, the top and diagonal edges of the window were encapsulated to provide additional rigidity. For this design, the weather-stripping was removed as shown in Figures 3.1 and 3.2.





3.3 Modified Side Door Window Frame

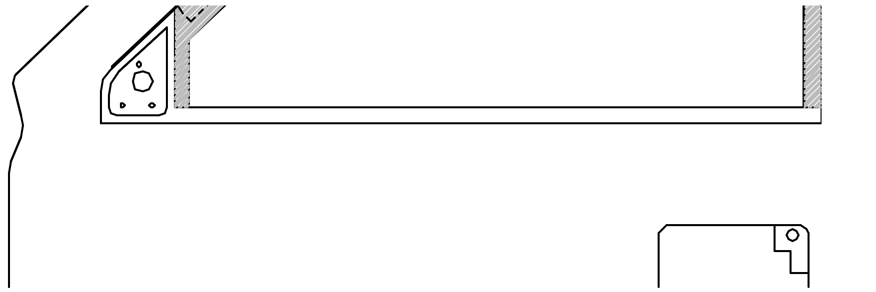
Modifications to the window frame were required to accommodate the modular glazings and to transfer the load to the vehicle door. A detailed explanation of the modifications to the Ford LTD window frame can be found in the first status report[1].

Initial C/K window frame modifications - The simplistic design of the C/K window frame along with the T-edge section afforded a simple modification in which 20-gauge sheet metal was bent around the interior and exterior sides of the C-channel and was welded in place. This modification was made along only the vertical edges of the frame above the belt line.

With the weather-stripping removed, the top and diagonal window edges rested against the door frame. Any loading would simply push these edges away, allowing an opening to occur. A U-channel of considerable depth was simulated by adding 20-gage sheet metal to the exterior and interior of the door/window frame. Edge engagement of the window frame was 33-35 mm along the top and diagonal edges. Initial impact testing pointed to failure mode at the transition of the diagonal and top edge, where the glazing lost engagement with the U-channel. Therefore, the U-channel depth was increased to 50-63 mm at this point. The resulting door window frame modification is shown in Figure 3.3. Although it was necessary to remove the weather-stripping, this modification did not restrict the window's ability to be raised and lowered.

Reduced C\K window frame modifications - The initial C/K door modifications resulted in a glazing system that demonstrated a feasible countermeasure to occupant ejection could be obtained (see chapters 4-6). Efforts were undertaken to reduce the amount of window frame modifications while still obtaining adequate retention under the developed impact test conditions. Any reduction in potential head injury was then investigated.

The added sheet metal on the interior side of the door frame was removed. The sheet metal on the exterior side was reduced, resulting in an edge capture of 19-22 mm along the top and diagonal edges. Once again, the transition of the top and diagonal edges proved to be the weak point. The edge capture at this transition point was increased to 32 mm. The modifications to the vertical edges were left unchanged. The resulting door/window modifications are shown in Figure 3.4.



4.0 OCCUPANT RETENTION ASSESSMENT

The primary goal for an advanced glazing system is to increase occupant retention in vehicle crashes, thereby reducing the number of deaths and injuries due to ejection. In order to measure the ejection mitigating potential of a glazing system, it was first necessary to develop test procedures for this purpose. The glazing systems were then tested using these procedures, and the results were evaluated. This chapter describes these efforts.

4.1 Test Procedure Development

Occupant ejection involves a secondary collision with the window systems. Establishing these secondary impact conditions was critical for determining the required strength of the side glazing systems. The stronger the glazing, the higher its retention capability, but increased strength may also present a higher potential for producing head and neck injuries. Several techniques were used to evaluate the type of impact conditions that can produce occupant ejection. Once the real world conditions were established, a series of tests were conducted to determine the best method for reproducing the crash conditions in a repeatable laboratory environment. This test development effort involved analysis of crash test films, real world crash data, computer simulations, pendulum and HYGE sled testing, and component impactor testing. Detailed explanations of these efforts were reported in Chapters 6 and 7 of the first status report[1], so only a summary of this work is presented here.

A series of crash simulations were conducted to evaluate occupant kinematics in rollover and side impact crashes. These simulations were based on NASS investigated crashes and focused on establishing the body regions that contacted the windows and the speeds at which they hit. All available high speed films of rollover tests were used to measured occupant shoulder to glazing contacts speeds. These impacts were measured from 2.5 to 31.3 kmph (1.6 to 19.5 mph). For side impacts, where test films were not suitable for analysis, the NASS crash data were analyzed for vehicle lateral change in velocity (v) in crashes involving side glazing disintegration due to occupant contact[6]. These v's represent an upper bound for the speed of the occupant to glazing contact speed and ranged from 0 to 56.3 kmph (35.0 mph), averaging 17.8 kmph (11.1 mph). The single most frequent side impact v was about 30 kmph (19 mph), accounting for over 20% of all cases examined.

The glazing systems were commonly struck by the occupant's head and shoulder. A retention test would have to simulate the worse case conditions of an occupant's head and shoulder striking the glazing simultaneously. A series of pendulum tests were used to establish the effective mass of a dummy's head and shoulder area. These initial estimates were further supported by a series of sled tests that measured the forces on a simulated door when struck by a dummy. Based on this test data and additional computer simulations, a mass of 18 kg (40 lb) was selected.

A component test impactor was designed for use inside a vehicle to evaluate the occupant retention capability of advanced side glazings (see Figure 4.1). Retention capability would be evaluated based on a dynamic deflection measurement of the guided impactor. An existing featureless free-motion headform (FFMH) was selected for the impactor face. This rigid headform was originally designed for the upper interior head protection research program. It averages the dimensional and inertial characteristics of the frontal and lateral regions of the head into a single headform[8]. Because the weight of the retention test device was considerably higher than the weight of a typical human head, it was not suitable for evaluating any potential for causing head injury. Therefore, a second impact test was necessary to insure that glazing systems designed to prevent ejection would not present a head injury hazard (see Chapter 5). Knowing the potential head injury is particularly important since ejection almost exclusively occurs for unbelted occupants, while any potential for increased injuries would occur for all occupants, belted and unbelted.

Preliminary testing of advanced glazing systems in a Ford LTD door with the retention impactor demonstrated that adequate retention was maintained in the area of encapsulation, but that the unsupported (non-encapsulated) edges were subject to large dynamic deflections.

4.2 Occupant Retention Testing

A series of impact tests using the 18 kg retention impactor was conducted on the C/K Pickup door/ advanced glazing systems with several variations of T-edge encapsulation. The testing focused on the capability of retaining the glazing material in the window frame without failure of the encapsulation or the door window frame modifications. Typical test conditions are shown in figures 4.2 And 4.3.

Several variations to the window encapsulation and the frame were tested and analyzed. The modifications were all intended to prevent the top and diagonal edges of the window from being pushed out and thereby providing an ejection path. The encapsulation modifications included adding a steel reinforcing rod to various places in the mold and replacing the polyurethane molded along the top and diagonal edges with a clear polycarbonate strip of various widths. This last modification was thought to increase the aesthetics of a framed side window. Variations in the door window frame included varying the depth of the U-channel along the top and diagonal edges and increasing the channel depth at the transition between the top and diagonal edges. For each test, the bottom edge of the window was constrained by the standard C/K window regulator. The retention performance of the glazing systems was strongly dependent upon the level of modification to the door frame. Minimal modification to the stock door frame did not adequately retain the impactor, while tests with significant U-channels provided excellent retention. The door frame modifications were primarily designed to enhance occupant retention. Production capability and consumer acceptability were considered but not evaluated. This test program focused on the feasibility of using door/glazing systems to mitigate ejection.

Establishing performance criteria for the retention test presented a bit of a challenge. All of the glazing systems were able to stop the impactor's motion before reaching the physical 'stops' on the impactor's guidance system. However, it was not uncommon for a large percentage of the window's periphery to have pulled free of the window frame. This condition would leave sufficient space for a head or arm to potentially be partially ejected through the window. Two performance criteria were established for the retention test: the maximum deflection of the impactor, and the percentage of the window periphery that remained within the window frame. A linear potentiometer recorded the displacement of the impactor measured from first contact with the glazing through maximum dynamic displacement. This measurement was a combination of both the deflection of the glazing material and the door window frame. A second measurement of the containment percentage was calculated by measuring the amount of glazing/encapsulation mold that had pulled free from the window frame along the top and diagonal edges and the vertical A and B-pillar edges. The bottom edge always remained firmly attached to the window regulator throughout the test matrix. Any penetration of the impactor and resulting tearing of the plastic material is noted separately. These criteria were used to evaluate the performance of the glazing / door system retention performance.

Additional tests were conducted to evaluate the retention performance of damaged door systems. In both side impact and rollover crashes, the door is likely to have been damaged prior to occupant contact. A series of door/glazing systems were subjected to quasi-static roof crush tests and were then impacted using the retention impactor. For the door/glazing systems tested, the overall performance of the damaged systems was similar to that for the undamaged systems.

The feasibility of using advanced glazing systems to prevent occupant ejection depends heavily on the practicability of the proposed door modifications. One obvious problem with the proposed designs is they are not applicable to vehicles with frameless side windows. In particular, convertibles and vehicles with removable t-top roofs do not generally have window frames and the proposed designs are not applicable to these vehicles. It is difficult to determine the exact number of vehicles that have frameless windows, but there is a significant minority of passenger cars which have minimal, backless or no window frame. For this group of vehicles, the proposed door modifications would either require significant redesign or would not be applicable. For the majority of vehicles with framed windows, these retention tests have demonstrated the feasibility of using door / glazing systems to mitigate occupant ejection.

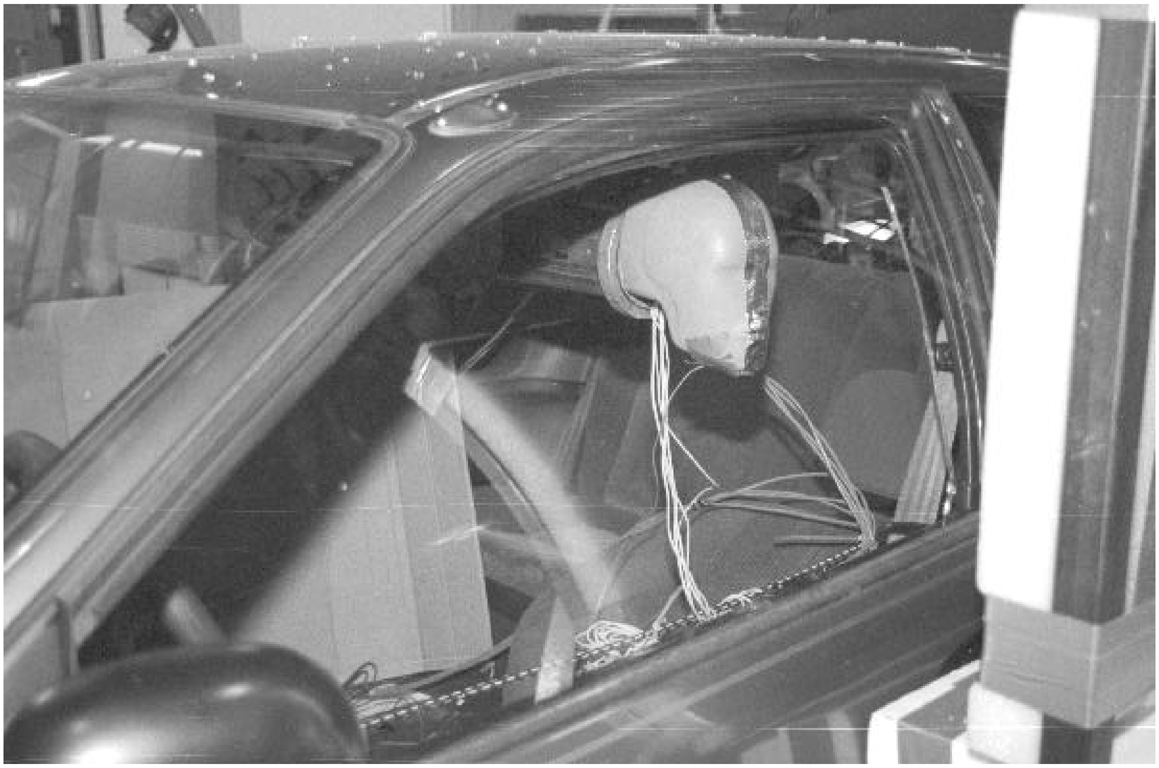
5.0 HEAD INJURY ASSESSMENT

The tempered glass used in most automotive side windows is designed to be a brittle material that shatters into numerous small pieces when impacted or deformed. In most side impact and rollover crashes, the tempered window glazing shatters prior to occupant contact. The introduction of ejection resistant glazing systems presents an additional surface for an occupant's head to contact. It is highly desirable to evaluate and minimize any potential injuries due to the introduction of ejection resistant glazing systems.

5.1 Test Description and Results

A series of free-motion headform (FMH) tests were conducted on the advanced glazing systems and standard tempered glass side windows. In addition to the C/K Pickup, tempered side windows from a 1993 Honda Civic and 1991 Dodge Caravan were also tested. The FMH was developed for use in the 1995 upgrade of FMVSS 201 "Occupant Protection in Interior Impact"[9]. This impact test is designed to evaluate the potential for head injury from impacts with the front and side headers, A pillar, and roof. The FMH is a Hybrid III head, weighing 4.5 kg (10 lbs.), modified for use as a free-motion impactor. The headform was instrumented with a triaxial accelerometer array located at the center of gravity. The head injury criterion (HIC) is computed from these measurements to estimate the probability of occupant injury.

The test setup consisted of the glazing/door system, mounted to the vehicle, and the impactor (see Figure 5.1). This setup simulated real world conditions by allowing the dynamic deflection of the door frame. For each glazing type and impact location, multiple tests were conducted to generate an understanding of the repeatability of this type of glazing testing.



The most important conclusion from these FMH tests was that the advanced glazings tested did not significantly increase the head injury potential over standard tempered glass side windows. The highest HICs recorded were from impacts to the standard Civic tempered side window. In these two tests, the glazing did not break, and HICs of 423 and 428 were produced. The next highest HICs were from impacts to the center of the polycarbonate glazing, which also did not fracture, and resulted in HICs of 399 and 368, (None of these HIC measurements is close to the critical HIC value of 1000 specified in FMVSS 201). Therefore, it does not appear that these advanced side glazings present a higher risk of head injury than side glazings currently in use.

For any given glazing and impact configuration, the HIC responses were higher if the glass did not break. The HIC responses were from 38 to 74 percent lower in the tests which produced glass fracture as compared to those that did not (based on average HICs). For a given glazing system and set of impact conditions, it is likely that maximum (or near maximum) HIC is achieved at the speed just below that which produces glazing fracture, and that increasing the impact speed in subsequent tests may not result in substantially higher HICs.

The impacts in the upper rear corner of the glazing (near the B-pillar) were less likely to produce glazing fracture than impacts to the center of the glazing. Generally, it appears that the proximity of the door frame to the upper rear corner impact location helped to distribute a portion of the impact force to the door frame, thereby stressing the glazing less, resulting in fewer fractures than in impacts to the center location. The upper corner location often produced higher HICs than the center location, since an upper corner impact was less likely to result in glazing fracture.

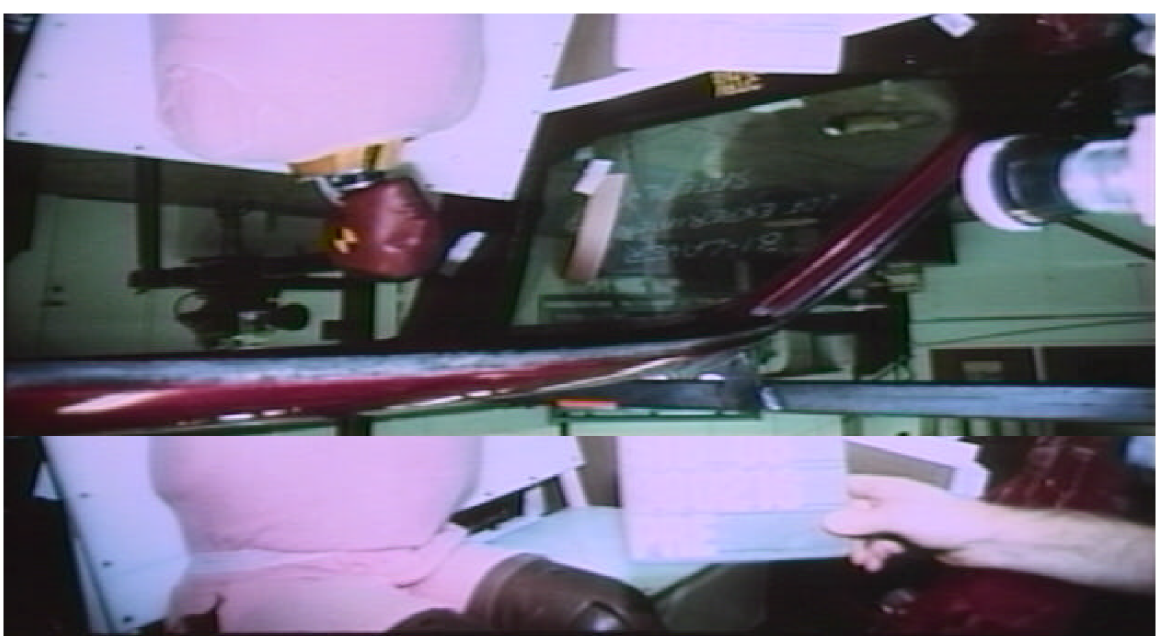
Finally, a number of repeat tests were conducted to evaluate the repeatability of the test procedure. In cases where repeat tests produced different fracture results (i.e. some fractured while others did not), there were generally large differences in the resulting HICs. Since impact speeds were consistent, it was felt that this variation was largely due to variations in the glazing material and not the test procedure itself. The average coefficient of variation (c.v.) for the repeat tests was 15.2 percent, which doesn't indicate good repeatability. Several of these had very low average HICs in which even small differences result in a relatively higher percentage variation. When only the tests which produced an average HIC of 200 or more were considered, the average c.v. was 7.7 percent, which is considered good. Even when this sampling was expanded to include sets of tests with an average HIC of at least 150, the average c.v only rose to 12.0 percent, which is still acceptable.

The FMH testing showed low potential for head injury from occupant to glazing impacts. The head injury potential from impacting the advanced glazing systems were within the range of responses for similar impacts into tempered side windows.

6.0 NECK INJURY ASSESSMENT

Previous full-vehicle tests conducted by NHTSA had raised some concerns regarding high lateral neck loads measured by the dummies in rollover and side impact tests. There was concern that the advanced glazing systems could increase neck loads from lateral impacts. Since the loading measured at the neck is determined by the relative motion between the head and shoulders, a component test is not appropriate. Instead, a series of HYGE sled tests were conducted to assess the potential for neck injury due to occupant contact with the advanced side glazing/modified doors. The approach was to compare the neck loads and moments of a full dummy from impacts into ejection mitigating glazings to those into standard tempered glass side windows.

The sled buck was similar to the test frame used in the component level testing (see Figure 6.1). It consisted of a C/K Pickup truck cab with a standard driver side door. The side door padding, arm rest, and trim were removed so that they would not interfere with the dummy's movement through the glazing area. A generic seat was fabricated that allowed the sled buck to accelerate under the dummy and strike the dummy at the specified speed. The SID/H-III anthropomorphic test device was chosen and instrumented with a six-axis upper neck load cell and accelerometers in the head, upper (T01) and lower (T12) spine, and upper and lower ribs.



The sled tests were conducted with the dummy tilted 26_ toward the window to maximize the loading on the neck. This seating position subjected the dummy's neck to three potentially injurious loading conditions: lateral shear, axial compression, and a moment about the longitudinal (x-) axis. In later tests, the seat was raised so that the head and shoulder would strike the window simultaneously. For all test conditions, the seat was moved forward to prevent any part of the dummy's head from striking the B pillar.

The dummy impact caused the glass to break in every test (the polycarbonate windows did not fracture) but the ejection mitigating glazings remained entirely within the modified door frame (i.e. 100 percent containment). The plastic inner layer was torn in both tests involving the non-HPR trilaminate but the head did not penetrate. The plastic inner layer remained intact in the HPR trilaminate configuration.

The repeatability of neck loads and moments was generally poor. The variation in repeat tests (i.e. plus or minus the percentage difference from average) averaged Å21.0 percent for the shear loads, Å16.3 percent for the axial loads, and Å15.1 percent for the moments. In each case, the responses from the tempered glass impacts were the least repeatable, with variations of Å64.0 percent, Å46.5 percent, and Å30.0 percent for the shear loads, axial loads, and moments, respectively. In fact, the lowest axial neck load measured in all the sled tests was 1553 N in one of the tempered glass impacts, while the second highest was 4253 N, from the repeat of that test. Unlike for the FMH tests discussed in the previous section, it cannot be reasonably assumed that this variability was due largely to the glazing systems themselves. While they were certainly one source of variability, the test procedure itself had a number of variables which could have contributed.

Despite the high variability and limited data, a few observations can be made regarding these tests. Generally, impacts into standard tempered glass resulted in lower neck shear loads and neck moments than those into the advanced glazings. In each case, the lowest responses measured were from the tempered glass impacts. Impacts into standard tempered glass resulted in axial loads that were comparable to those into the advanced glazings. No assessment of actual neck injury levels due to shear loads or moments was made since no accepted lateral neck injury criteria exist.

7.0 BENEFITS

This section provides estimates of the safety benefits of installing encapsulated advanced glazing in light vehicles and provides a sensitivity study to examine the impact of increased seat belt use on advanced glazing benefits. The basic benefit estimation procedure consisted of the following steps: (1) Establish baseline ejection population; i.e., the number of occupants ejected through closed or partially opened windows and in which advanced glazing would hold; (2) Estimate the number of fatalities and incapacitating injuries that would be prevented; (3) Redistribute the estimated fatal and incapacitating injuries that would be reduced to less serious injury levels; (4) Calculate the net benefits.

The 1995-1999 Crashworthiness Data System (CDS) and Fatality Analysis Reporting System (FARS) were used for the analysis. In step 1, the occupant retention rates are essential to calculate the baseline ejection population. The occupant retention rates of glazing were derived from a hard copy review of CDS cases. A team of engineers reviewed and cross reviewed a sample of CDS ejection cases to ascertain the percentage of ejections that would be prevented by advanced glazing. The retention rate is a function of intrusion magnitude and weighted by crash severity. Based on 1995-1999 CDS, the overall retention rate is 21 to 52 percent with 20 to 49 percent for front side windows and 28 to 68 percent for back side windows.

In step 2, a double-pair comparison methodology was used to compare relative injury rates among the ejected and non-ejected occupants by various injury severity levels and occupant types. The fatality and incapacitating injury reduction rates then were calculated. These reduction rates were applied to the corresponding baseline population to calculate the number of fatalities and incapacitating injuries prevented. The double-pair comparison and related techniques to estimate the benefits when ejection is eliminated are described in the NHTSA's technical report "Estimating the Injury-Reducing Benefits of Ejection-Mitigating Glazing"[4].

In step 3, it was assumed that the effect of ejection prevention by the advanced glazing is the same as the effect of being prevented from ejection by other elements of the vehicle interior. Thus, to distribute the fatalities or injuries prevented to the less severe injuries, the distribution of injuries among non-ejected occupants of motor vehicles in accidents involving ejections was used as an estimate of the distribution of injuries among non-ejected occupants when the advanced glazing is in place.

Finally in step 4, the benefits are estimated. After completing step 3 - distributing the fatalities and injuries prevented to less severe injuries, a new injury distribution was established. The estimated net benefits is the difference between the initial baseline injury distribution and the new injury distribution.

The following sections 7.1 to 7.3 present a range of estimated benefits. Section 7.1 reports the safety benefits from front side glazing and Section 7.2 from the back side glazing. Section 7.3 summarizes the overall glazing benefits. The upper bounds of the benefits correspond to the higher retention rates, while the lower bounds of benefits correspond to the lower retention rates.

7.1 Benefits From Front Side Advanced Glazing

The baseline ejection population included all the ejections from front side windows of light vehicles in which glazing was either closed or partially opened before impact where the ejections would have potential to be prevented by advanced glazing. Data from the 1995-1999 NASS CDS were used to derive baseline fatalities and injuries and retention rates. The retention rate for front side glazing was estimated to be 20 to 49 percent. The most recent 5 years of data were used to reflect the change in seat belt usage and to reduce sampling variation. CDS-derived fatalities then were adjusted to the annualized level in the FARS for the same period to overcome the underestimation of fatalities in CDS. Table 7.1 presents the baseline population. Table 7.2 presents the estimated benefits.

Baseline Ejection Population

As shown in Table 7.1, if 49 percent of the glazing had remained in place during the ejection-related crash, a total of 9,850 occupants ejected out front side windows would have been prevented. Of the ejected occupants that could be preventable, 2,287 (23 percent) were using a seat belt, 7,563 (77 percent) were not. A total of 1,486 (15 percent) of the ejected occupants were fatally injured and 2,289 (23 percent) incurred nonfatal serious injuries (MAIS 3-5).

If 20 percent of the glazing had remained in place during the ejection-related crash, a total of 4,040 occupants ejected out front side windows would have been prevented. Of the ejected occupants that could be preventable, 939 (23 percent) were using a seat belt, 3,101 (77 percent) were not. A total of 611 (15 percent) of the ejected occupants were fatally injured and 938 (23 percent) incurred nonfatal serious injuries (MAIS 3-5).

Table 7.1
Estimated Annual Number of Ejections Prevented
Through Closed or Partially-Closed Front Side Windows of Light Vehicles
in Which Advanced Glazing Would Have Remained In Place
by Belt Use, Injury Severity, and Retention Rate

	for 49 Percent Occupant Retention Rate			for 20 Percent Occupant Retention Rate		
	Restraint Usage			Restraint Usage		
	Yes	No	Total	Yes	No	Total
MAIS=0	58	146	204	24	60	84
MAIS 1-2	1,899	3,972	5,871	779	1,628	2,407
MAIS 3-5	218	2,071	2,289	89	849	938
FATAL*	112	1,374	1,486	47	564	611
TOTAL	2,287	7,563	9,850	939	3,101	4,040

Source: 1995-1999 CDS; 1995-1999 FARS

* Fatalities derived from 1995-1999 NASS CDS were adjusted to the annualized level in FARS.

Net Safety Benefits

An estimated 423 to 1,031 fatalities and 227 to 557 serious (MAIS 3-5) injuries (see Table 7.2) could be prevented by installing advanced glazing in the front side windows of light vehicles. The higher bounds of the benefits correspond to the 49 percent retention rate, while the lower bounds are for the 20 percent retention rate.

Table 7.2
Estimated Net Safety Benefits of Front Side Advanced Glazing

Injury Severity	for 49 Percent Occupant Retention Rate	for 20 Percent Occupant Retention Rate
MAIS 3-5	557	227
FATAL	1,031	423

7.2 Benefits From Back Side Advanced Glazing

The analysis applies the same benefit estimating procedure described in the previous subsection to derive the benefits for back side glazing. Based on the 1995-1999 CDS and FARS, ejections from back side windows had a different crash severity profile than those from front side windows. The weights used to estimate the overall retention rate for back side glazing therefore, are different from those of front side windows. The derived occupant retention rates for back side windows ranged from 28 to 68 percent.

Baseline Population

Table 7.3 shows the annual baseline ejection population from back side glazing where the advanced glazing would have held during the crashes. For the 68 percent retention rate, about 2,502 ejections would be prevented by advanced glazing in the back side windows. Of these, 2,421 (97 percent) of these ejected occupants were unrestrained. For the 20 percent retention rate, about 1,027 ejections would be prevented by advanced glazing in the back side windows. Of these, 994 (97 percent) of these ejected occupants were unrestrained.

Table 7.3
Estimated Annual Number of Ejections Prevented
Through Closed or Partially-Closed Back Side Windows of Light Vehicles
in Which the Advanced Glazing Would Have Remained in Place
by Belt Use, Injury Severity, and Retention Rate

Injury Severity	for 68 Percent Occupant Retention Rate			for 28 Percent Occupant Retention Rate		
	Restraint Usage			Restraint Usage		
	Yes	No	Total	Yes	No	Total
MAIS=0	0	2	2	0	1	1
MAIS 1-2	49	1,900	1,949	20	780	800
MAIS 3-5	18	133	151	7	54	61
FATAL*	14	386	400	6	159	165
TOTAL	81	2,421	2,502	33	994	1,027

Source: 1995-1999 CDS; 1995-1999 FARS
* Fatalities derived from 1995-1999 NASS CDS were adjusted to the annualized level in FARS.
Note: the results have greater variations because of small sample.

Net Safety Benefits

Table 7.4 shows the estimated benefits, 114 to 274 fatalities and 8 to 18 serious (MAIS 3-5) injuries could be prevented by installing advanced glazing in the back side windows of light vehicles. The higher bounds of the benefits correspond to the 68 percent retention rate, while the lower bounds are for the 28 percent retention rate.

Table 7.4
Estimated Safety Benefits of Back Side Advanced Glazing

Injury Severity	for 68 Percent Occupant Retention Rate	for 28 Percent Occupant Retention Rate
MAIS 3-5	18	8
FATAL	274	114

Note: the results have greater variations because of small sample.

7.3 Benefit Summary

This section presents Table 7.5 to summarize the combined benefits of front and back side advanced glazing. The higher bounds of benefits corresponds to a overall 52 percent (49 percent - front side windows, 68 percent - back side windows) retention rate. While the lower bound of advanced glazing benefits corresponds to the lower overall 21 percent retention rate (20 percent - front, 28 percent - back).

In total, if both front and back side windows had installed the advanced glazing, an estimated 537 to 1,305 fatalities and 235 to 575 serious (MAIS 3-5) injuries could be prevented annually.

Table 7.5
Estimated Safety Benefits for Advanced Glazing

Front Side Glazing	Injury Severity	Higher Bounds	Lower Bounds
	MAIS 3-5	557	227
	Fatal	1,031	423
Back Side Glazing	MAIS 3-5	18	8
	Fatal	274	114
Front and Back Side Glazing Combined	MAIS 3-5	575	235
	Fatal	1,305	537

Note: Retention Rates: 20 - 49% for front side glazing; 28 - 68% for back side glazing; 21 - 52% overall.

7.4 Sensitivity Study

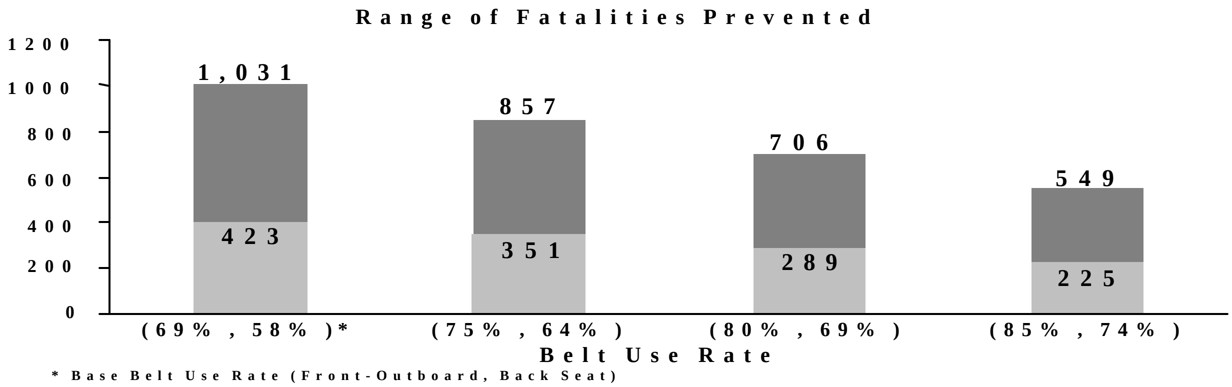
This section estimates the change in benefits that could result from increased seat belt use. Based on the 1995-1999 State Observation Belt Use Surveys, the belt usage rates for front-outboard occupants stayed steady over the time period. The average belt use in these 5 years was 69 percent. The 69 percent is the base belt use rate for front-outboard occupants in this analysis. There is no seat belt use survey data among back seat occupants for the comparable years. The 1994 NOPUS is the most current survey on belt use among back seat occupants. The analysis does not use the NOPUS estimates because the survey is old and might not reflect the belt use trend in recent years. Instead, the analysis derived the belt use among back seat occupants by adjusting the belt use rates in 1995-1999 CDS (survivors) and FARS (fatalities). The adjustment is made assuming that the relationship of back seat belt use in the crash system and in the general population is the same as that of front-outboard occupants. As a result, the average back seat belt use in the general population from 1995 to 1999 was 58 percent. Thus, the baseline benefits of advanced glazing which were estimated in the previous sections were at base belt use rates of 69 percent for front-outboard occupants and 58 percent for back seat occupants. The sensitivity study examines the net benefits for the advanced glazing at the 75, 80, and 85 percent of belt use levels for front-outboard occupants and 64, 69, and 74 percent for back seat occupants. The benefit results are reported for three combinations (front, back) of belt use among front-outboard and back seat occupants: (75 percent, 64 percent), (80 percent, 69 percent), and (85 percent, 74 percent). These three levels correspond a 6, 11, and 16 percentage point increase from the base (69 percent, 58 percent), respectively. In other words, the analysis assumes that within a specific time frame, the seat belt use among the front-outboard and the back seat occupants would increase the same number of percentage points from their base belt use rates.

The benefit assessment at each new belt use level includes the four step process described earlier: (1) establishing a baseline, (2) estimating fatalities and incapacitating injuries prevented, (3) redistributing those fatalities and injuries prevented to a lesser severe injuries, and (4) estimating the net benefits. In order to derive the adjusted baseline population, it was necessary to determine what portion of the baseline population ejections would actually be prevented by increased seat belt use. NHTSA's belt usage software (BELTUSE) program* (Blincoe, 1994)[6] was used to estimate the overall incremental benefits (ejections and non-ejections) from increased seat belt use. The ejection portion of the incremental benefits is assumed to be equivalent to the percent of ejections reported in the unbelted occupants. The difference between the baseline population and the increment seat belt impacts is the adjusted baseline population. After adjusting the baseline population, the analysis follows the benefit estimate process step 2 to step 4 to assess the net benefits of glazing at three specified belt use levels.

As shown in Figure 7-1, the front side advanced glazing would prevent from 351-857 fatalities and 200-486 serious injuries (MAIS 3-5) at the combination belt use of (75 percent, 64 percent), 289-706 fatalities and 172-418 serious injuries at (80 percent, 69 percent), and 225-549 fatalities and 143-351 at (85 percent, 69 percent).

Figure 7-2 shows only the fatalities benefits from back side advanced glazing. The back side advanced glazing would prevent from 93-226 fatalities at the combination belt use of (75 percent, 64 percent), 76-186 fatalities at (80 percent, 69 percent), and 59-144 fatalities at (85 percent, 69 percent). The serious injury benefits were not shown because the sample is too small to be reliable.

Overall, the front and back side advanced glazing (Figure 7-3) would prevent from 444-1,083 fatalities and 197-479 serious injuries if the belt use rate was at the combination of (75 percent, 64 percent), 365-892 fatalities and 169-409 serious injuries at (80 percent, 69 percent), and 284-693 fatalities and 140-342 serious injuries at (85 percent, 69 percent).



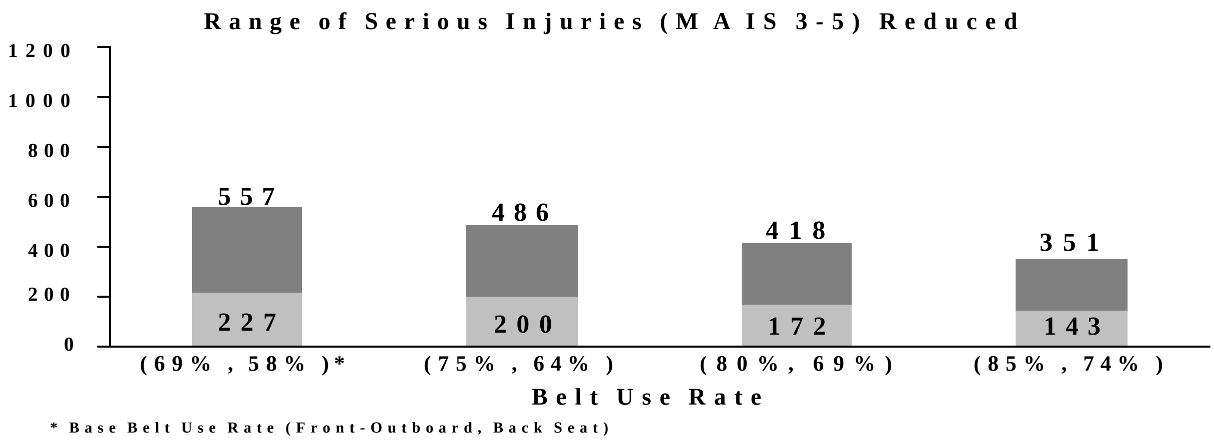


Figure 7-1 Estimated Fatalities and Serious Injuries Prevented From Front Side Advanced Glazing by Specified Belt Use Levels

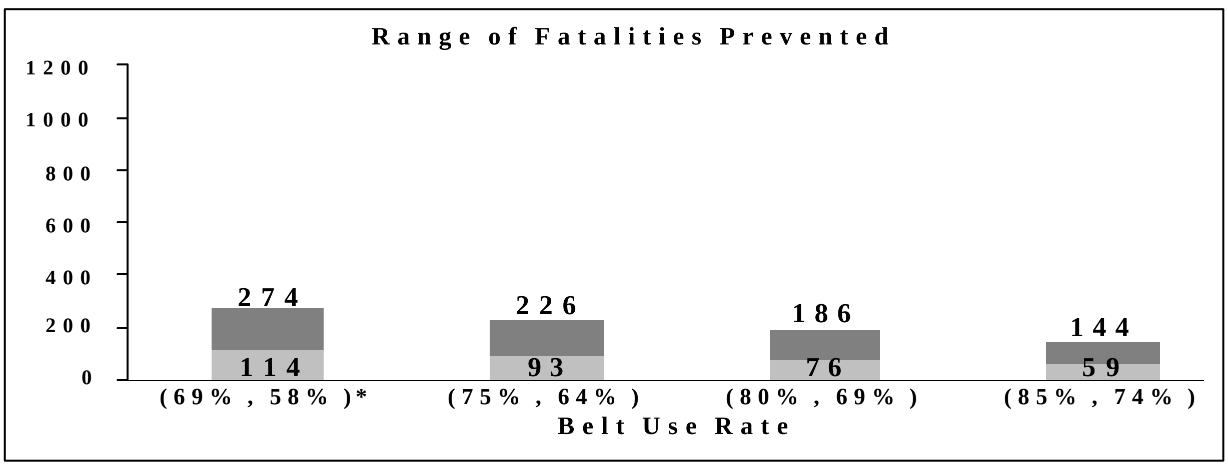
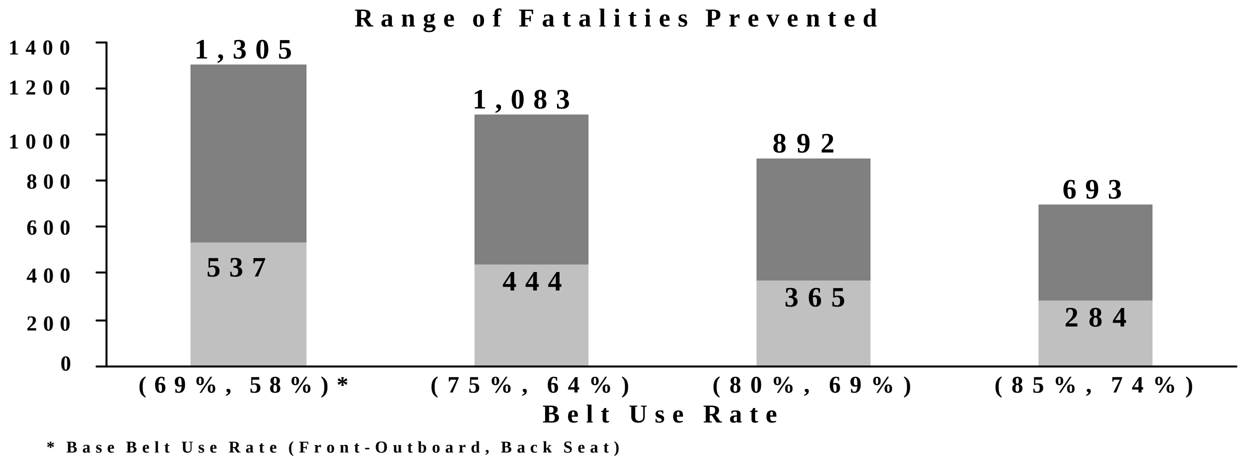


Figure 7-2 Estimated Fatalities Prevented from Back Side Advanced Glazing by Specified Belt Use Levels



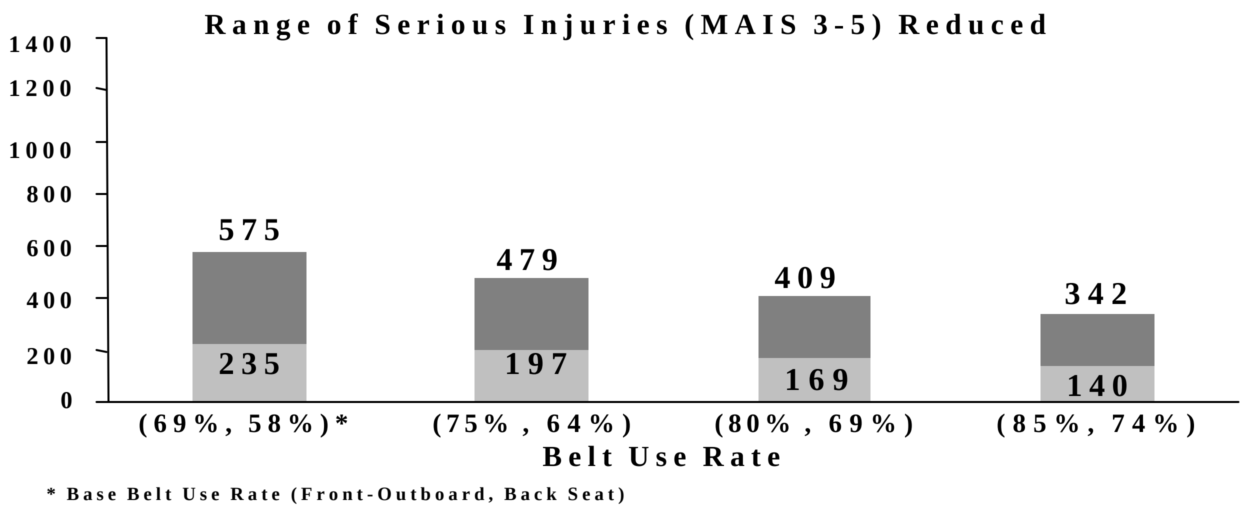


Figure 7.3 Estimated Fatalities Prevented from Front and Back Side Advanced Glazing Combined by Specified Belt Use Levels

8. 0 COST

This section evaluates the cost of the proposed advanced glazing systems. The 1995 Status report estimated the costs. Since then, the glazing team has not yet revisited the cost issue. In addition, there are no cost estimates for back side windows. Thus, this section only discusses the costs for front side windows. The incremental cost estimated in the 1995 status report was between $48 and $79 per vehicle to modify the two front side windows. This cost estimate was developed for vehicles with framed windows only and reflects the prototype design used in the 1995 status report. This cost figure is very sensitive to the vehicle door/window frame designs and crash test conditions.

To obtain a rough estimate of the annual consumer cost of installing advanced glazing in the front side windows of the light vehicle fleet with the 1995 prototype, it was assumed that the costs for a 1995 Ford Taurus would be the average cost for all light vehicles. Further, it was estimated that annual sales of new cars and light trucks would total 17 million units (8.0 million passenger cars and 9.0 million light trucks; approximate trend projection detail, Table 6, "The U.S. Economy, The 25 Years Focus", Winter 2000)[7] in the year 2005-2006 time frame when any requirement for advanced glazing might be implemented. As presented in column 3 of Table 8.1, the estimated annual consumer cost of installing advanced glazing in the front side windows of new light vehicles would range from $816,000,000 to $1,349,000,000, depending on the type of glazing installed. Note that the report uses uninflated 1995 costs because the research team believes the estimated price of installing advanced glazing in 1997 dollar value would be very similar to that in 1995 dollar value due to low inflation, material technology advancement, and manufacturer process improvement. The projected leadtime estimated by Management Engineering Associates (MEA) in 1995 for phase-in of advanced glazing for new vehicles was about 3 years. A research report on overall ejection mitigation technologies will update the costs, weight analysis, leadtime, and incremental capital equipment estimates.

Table 8.1 – Estimated Incremental Cost for Ejection Mitigating Glazing Installed in Front Side Windows

Type of Advanced Glazing	Estimated Consumer per Vehicle Cost of Advanced Glazing in Front Side Windows	Estimated Annual Consumer Cost of Installing Advanced Glazing in New Light Vehicles*
Trilayer Glass	$48.00	$816,000,000
Dupont "Sentry Glas"	$50.50	$858,500,000
St Gobain Bilayer	$51.34	$872,780,000
Rigid Plastic	$79.38	$1,349,460,000

* The estimates are based on light vehicle annual sales of 17 million units in the 2005-2006 timeframe.

The cost of advanced glazing would be incurred by consumers at the time of vehicle purchase in the form of higher sales prices. On the other hand, the ejection mitigation benefits of advanced glazing would accrue over the operating lives of the vehicles they purchase. The benefits realized would be confined to safety benefits; advanced glazing and other "crashworthiness" technologies do not provide vehicle property damage or other categories of savings associated with crashes being prevented, as do "crash avoidance" technologies, such as advanced brake systems, center high mounted stop lamps, and vehicle modifications that improve driver visibility. Vehicles equipped with advanced glazing would still be heavily damaged in ejection-producing collisions. In fact, the window replacement costs would be increased due to the higher cost of advanced glazing. Property damage loss and the expense associated with congestion, police investigation, and site cleanup would still exist.

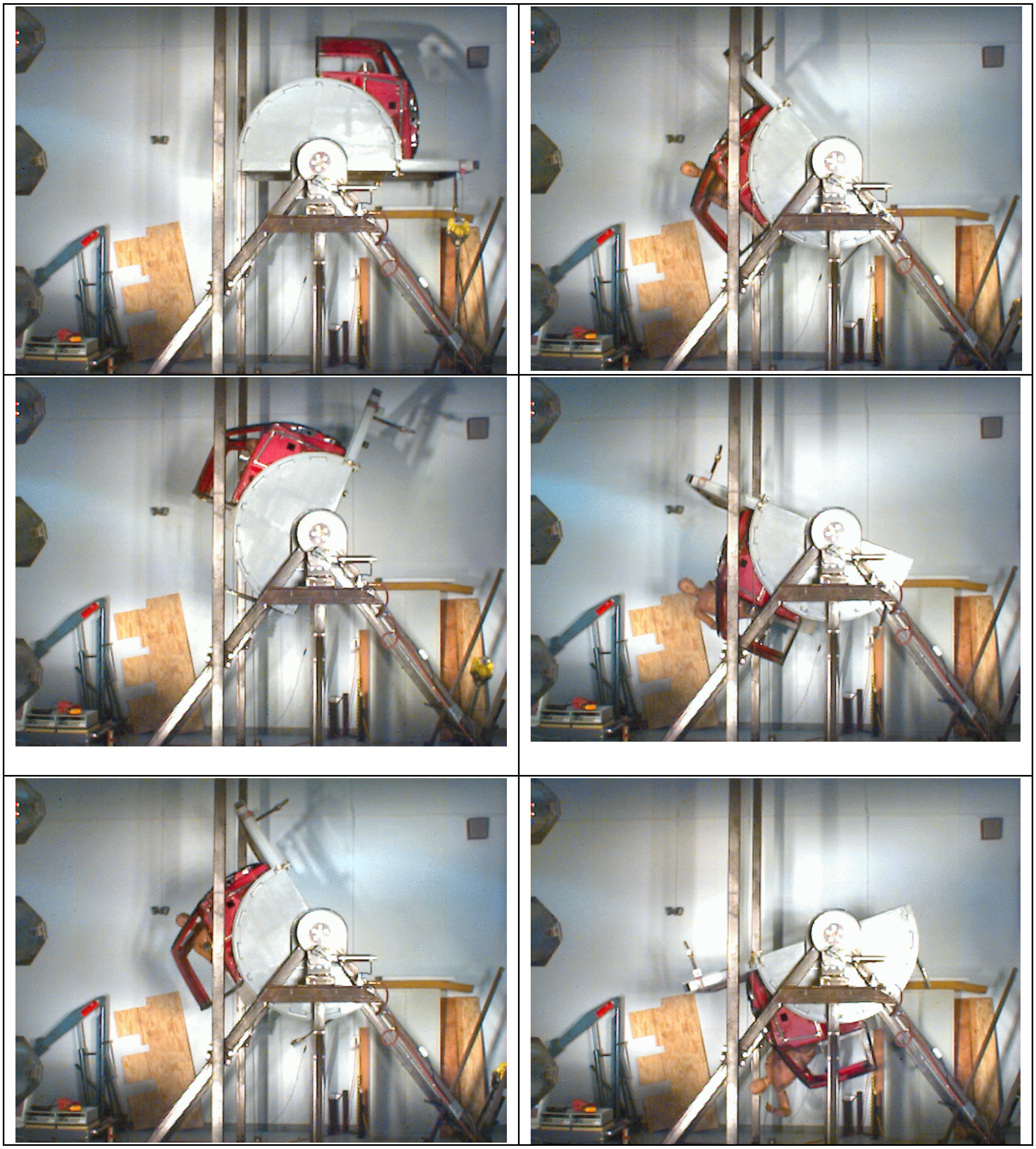
Note that the cost of installing of advanced glazing is very sensitive to the vehicle door/window frame design. The design variation would depend on the retention impactor test speed. At publication of this report, the advanced glazing research team has not yet finalized the retention impactor test procedure or conducted an updated cost estimate. Thus, the report does not provide cost-effectiveness estimates. However, before conducting a cost-effectiveness analysis, the advanced glazing benefits must first be discounted back to a present value.

9. EVALUATION OF ADDITIONAL EJECTION MITIGATION COUNTERMEASURES

Automotive manufacturers and suppliers have proposed using side inflatable devices to provide both occupant ejection mitigation and head impact protection. To evaluate the feasibility of this concept, NHTSA conducted four full-scale rollover tests using prototype inflatable devices provided by Simula ASD, and TRW Vehicle Safety Systems, Inc. The results from the first three tests were presented at the 1998 ESV conference[10]. The four FMVSS 208 dolly rollover tests were conducted on 1993 and 1994 Ford Explorer sport utility vehicles. Each vehicle was equipped with side inflatable devices adjacent to both front passenger seating positions. These devices were all prototype systems and each test utilized a different device design. All of the tests contained hybrid III dummies in the driver and right front passenger seating positions. All of the dummies were unbelted, except the passenger dummy in the third test. In each of the tests, there was considerable contact between dummies and the side inflatable devices. Subsequent computer simulations for two of the tests predicted that complete driver ejections would have occurred without the air bag. While successful at preventing complete ejection in all cases, 5 of the 8 dummies had an arm outside the vehicle during the rollover. These full-scale tests also showed that there was some potential for neck injury for non-ejected occupants. The final two tests also evaluated the performance of prototype rollover sensor systems developed by Simula and TRW. Both systems were successful in detecting the rollover and firing the airbags. These full-scale tests established the feasibility of using side inflatable devices to prevent ejection through front side windows.

The full-scale tests are not repeatable and cannot be used to optimize or compare side inflatable device designs. NHTSA has initiated a research program to develop a repeatable test method to simulate typical rollover occupant kinematics, which can be used in a controlled laboratory environment. A preliminary test device has been developed and is shown in Figures 9.1 through 9.6. This device has a rotating platform that can be rotated at realistic roll rates. Preliminary testing with the 50^{th} percentile male and 5^{th} percentile female dummies demonstrated occupant kinematics similar to full-scale testing. This research is currently underway and is expected to continue throughout fiscal year 2001.

NHTSA is also conducting tests to evaluate the suitability of the glazing retention test for use with side inflatable devices. The prototype devices tested to date are not intended to provide uniform coverage across the window opening and are therefore far more sensitive to the location or positioning of the impactor. NHTSA is evaluating the glazing retention impactor for use with current production side head air bags, designed only for side impact head protection, as well as with prototype systems that were designed to also mitigate occupant ejection. This research is also underway and expected to continue throughout fiscal year 2001.



10. SUMMARY

Ejection is a significant problem for automotive safety. In 1999, an analysis of FARS and NASS data produced estimates of 5,383 fatalities that involved ejection through the left- and right-front side windows. In rollover crashes, where the complex vehicle and occupant kinematics tend to defy most safety countermeasures, side window ejection mitigation is the most directly addressable safety problem. However, seatbelts currently provide excellent protection against ejection. Over 90% of all ejection fatalities are unbelted. Any safety countermeasure to prevent ejection would be a supplement to the primary protection provided by the seat belt.

Over the past 12 years, NHTSA has conducted an ongoing research program on preventing occupant ejection through the use of advanced side glazing systems. Ejection mitigating glazing systems involve the use of laminated glass and plastic windows inside of modified door frames, to withstand the force of occupant impact. A major aspect of the research involved demonstrating feasibility by developing and testing prototype systems. Since the technology within the automotive glazing industry has evolved considerably during the course of this research program, much of the research was only possible through the close cooperation of the glazing manufacturers. Custom glazing systems were developed in a variety of configurations to investigate possible safety benefits and consequences.

Developing the test methodology used to evaluate the prototype systems was another major focus of the research. The test method must provide repeatable and reproducible measurements that lead to better occupant retention in real world crashes. Since the benefits of ejection mitigation occur primarily for unbelted occupants, a critical factor in this research program was to investigate any possible disbenefits, particularly for belted occupants. The potential for head injury due to glazing impact was investigated using the FMVSS 201 impactor and the potential for neck injury was investigated using sled tests and dummy neck measurements. Finally, the research program evaluated the cost and safety benefits for the prototype glazing systems. The following is a summary of the primary research and findings presented in this report:

There were 32,091 fatalities among occupants of light vehicles in 1999, and 7,636 of them (24 percent) were ejected though glazing. Sixty percent of the occupants who were completely ejected through non-windshield glazing were ejected through a front side window. Partial or complete ejection through glazing accounted for an estimated 65 percent of the rollover fatalities in 1999.

Four types of advanced glazings were evaluated using the current test procedures. These were a non-high penetration resistant (HPR) trilaminate, an HPR trilaminate, a bilaminate, and a polycarbonate (rigid plastic). The side door window from a General Motors C/K Pickup was selected as the platform for this work, since the production version already included encapsulated vertical edges. In order to provide ejection mitigation capabilities, this encapsulation design was modified to incorporate a urethane T-edge on the vertical edges of the window. The corresponding vertical edges of the door window frame were also modified, by creating a C-channel to secure the T-edge, which maintained the window's ability to be raised and lowered. Through testing, it was found that modification of the top and diagonal edges of the window and corresponding door window frame was also necessary to provide adequate retention. Modifications to the top and diagonal edges of the window and the energy transfer through them, make this proposed design not applicable to vehicles with frameless windows.

A series of tests was conducted to refine the encapsulation/door window frame designs and to evaluate the retention capability of the various advanced glazings. The retention capability was assessed based on the glazing systems' capability to retain a guided, 18 kg (40 lb) impactor moving at 16 to 24 kmph (10 to 15 mph). To achieve retention, it was necessary to modify the top and diagonal edges of the door window frame by adding sheet metal to simulate a U-channel. The required level of top and diagonal door edge modification varied, depending on the type of glazing and the impact speed. The ejection resistance capability of the glazing systems were evaluated on penetration resistance, glazing containment, and maximum dynamic deflection during the impact test.

Free-motion headform (FMH) tests were performed for the purpose of assessing the head injury causing potential of advanced side glazing systems, as compared to current tempered glass side windows. A critical factor in determining the head injury causing potential of a glazing system may be the glazing's resistance to fracture. For a given glazing and impact configuration, the HIC response was higher if the glass did not fracture. The HIC responses were from 38 to 74 percent lower in tests which produced glazing fracture as compared to those that did not.

The advanced glazings tested did not necessarily produce higher HIC responses than the standard tempered glass side windows. Some impacts into advanced glazings did produce slightly higher HICs.

Repeatability of the FMH test procedure was good, but the repeatability of the glazing systems was not. Identical impacts frequently produced different fracture results, which generally resulted in large differences in the HIC responses.

HYGE sled tests were conducted to assess the potential for neck injury due to occupant contact with the advanced side glazing systems, as compared to standard tempered glass windows. The repeatability of the neck measurements were generally not good. Impacts into standard tempered glass resulted in lower shear loads and moments than those into the advanced glazings. Impacts into standard tempered glass resulted in axial loads that were comparable to those into the advanced glazings. In each case, despite the variability, the lowest responses measured were from the tempered glass impacts.

Advanced glazing systems could save 537 to 1,305 lives annually. Of these, 423 to 1,031 were prevented by front side glazing and 114 to 274 from back side glazing. In addition, an estimated 235 to 575 serious (MAIS 3-5) injuries would be reduced annually. These estimated benefits would be smaller if seat belt use increases in the future.

From the research conducted in this program and from the public comments received during the program, it appears that ejection-resistant glazing systems are a feasible safety countermeasure. The cost of the systems is expected to be significant, but not unreasonable considering the safety and other benefits provided by the advanced glazing systems. Testing did not indicate a significant risk of head injury from advanced glazing systems. The risk of neck injury is not well understood and requires considerable research, however these injuries are not frequently reported for ejected occupants. Depending upon the exact test requirements selected, the modifications to existing vehicle designs could be considerable, but should also incur significant safety benefits.

NHTSA is currently researching additional ejection countermeasures that appear to provide similar safety benefits. Preliminary full-scale testing with side inflatable devices was encouraging, but additional research is required to further evaluate this emerging technology. This includes the development of test methods for evaluating these devices. Currently, NHTSA is investigating the use of the glazing retention impactor for this purpose, as well as sled and rollover simulation testing. Ejection mitigation is the most significant safety issue in rollover crashworthiness, and through glazing research, NHTSA continues to improve occupant safety.

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